Jet Algorithms and Jet Reconstruction: Lessons from the Tevatron (A Continuing Saga)

(Thanks especially to Joey Huston & Matthias Tönnesmann)

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Outline

- Goals for Jet Algorithms
- Far Past (when life was inaccurate and easy)
- Recent Past at the Tevatron (life gets harder and more accurate)
- Future – impact on top reconstruction (true precision?)

The Goal is **1%** Strong Interaction Physics (where Tevatron Run I was ~ 10%)

Using Jet Algorithms we want to *precisely* map

- **What we can measure, *e.g.*, *E(y,ϕ)* in the detector**

On To

- **What we can calculate, *e.g.*, arising from small numbers of partons as functions of *E, y,ϕ***

***W*e "understand" what happens at the level of short distance partons and leptons, *i.e.*, pert theory is simple, can reconstruct masses, *etc*. (Don't need no darn MC@NLO!!)**

Thus

we want to map the observed (hadronic) final states onto a representation that mimics the kinematics of the energetic partons; ideally on a event-by-event basis.

But

we know that the (short-distance) partons shower (perturbatively) and hadronize (nonperturbatively), *i.e.*, spread out.

So associate "nearby" hadrons or partons into JETS (account for spreading)

- Nearby in angle – Cone Algorithms, *e.g.*, Snowmass (main focus here)

- Nearby in momentum space – k_T Algorithm

Renders PertThy IR & Collinear Safe

But mapping of hadrons to partons can *never* be 1 to 1, event-by-event!

colored states ≠ singlet states

Fundamental Issue – Compare Experiments to each other & to Theory

Warning:

We should all use the same algorithm!!
(as closely as humanly possible), *i.e.* both ATLAS & CMS (and theorists).

This is not the case at the Tevatron!!

In the Beginning - *Snowmass Cone Algorithm*

- **Cone Algorithm – particles, calorimeter towers, partons in cone of size R, defined in angular space, *e.g.*, (η,φ)**
- **CONE center - (η^C,φ^C)**
- **CONE i $\in$ *C iff*** $\sqrt{\left(\eta^i - \eta^C\right)^2 + \left(\varphi^i - \varphi^C\right)^2} \leq R$
- **Energy** $E_T^C = \sum_{i \subset C} E_T^i$
- **Centroid** $\overline{\eta}^C = \sum_{i \subset C} E_T^i * \eta^i / E_T^C \; ; \; \overline{\varphi}^C = \sum_{i \subset C} E_T^i * \varphi^i / E_T^C$

- **Jet is defined by "stable" cone**

$$\eta^J = \eta^C = \bar{\eta}^C \;\; ; \;\; \varphi^J = \varphi^C = \bar{\varphi}^C \;\; ; \;\; \vec{F}^C = 0$$

- **Stable cones found by iteration: start with cone anywhere (and, in principle, *everywhere*), calculate the centroid of this cone, put new cone at centroid, iterate until cone stops "flowing", *i.e.*, stable ⇒ Proto-jets (prior to split/merge)**

- ***"Flow vector"*** $\vec{F}^C = \left(\bar{\eta}^C - \eta^C, \bar{\varphi}^C - \varphi^C\right)$

⇒ *unique, discrete jets event-by-event* (at least in principle)

Run I Issues (Life gets more complex):

Cone: Seeds – only look for jets under brightest street lights, *i.e.*, near very active regions

⇒ problem for theory, IR sensitive at NNLO

Stable Cones found by iteration (E_T weighted centroid = geometric center) can Overlap,

⇒ require Splitting/Merging scheme
⇒ Different in different experiments

⇒ Don't find "possible" central jet between two well separated proto-jets (partons)

To understand the issues consider Snowmass "Potential"

- In terms of 2-D vector $\vec{r}=(\eta,\varphi)$ or (y,φ) define a potential

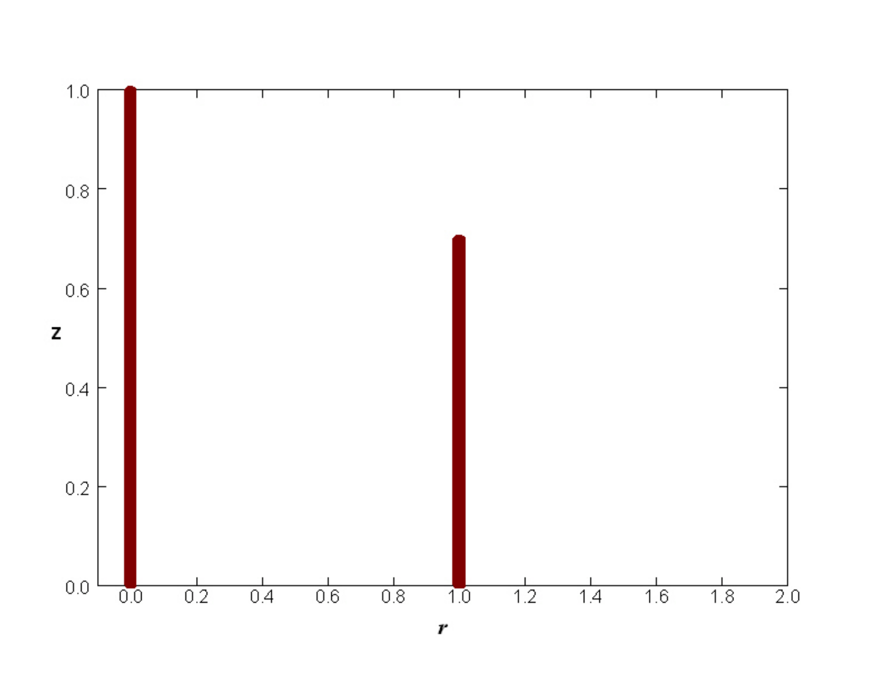
$$V(\vec{r}) \equiv -\frac{1}{2}\sum_i E_T^i \left(R^2-\left(\vec{r}^{\,i}-\vec{r}\right)^2\right)\Theta\left(R^2-\left(\vec{r}^{\,i}-\vec{r}\right)^2\right)$$

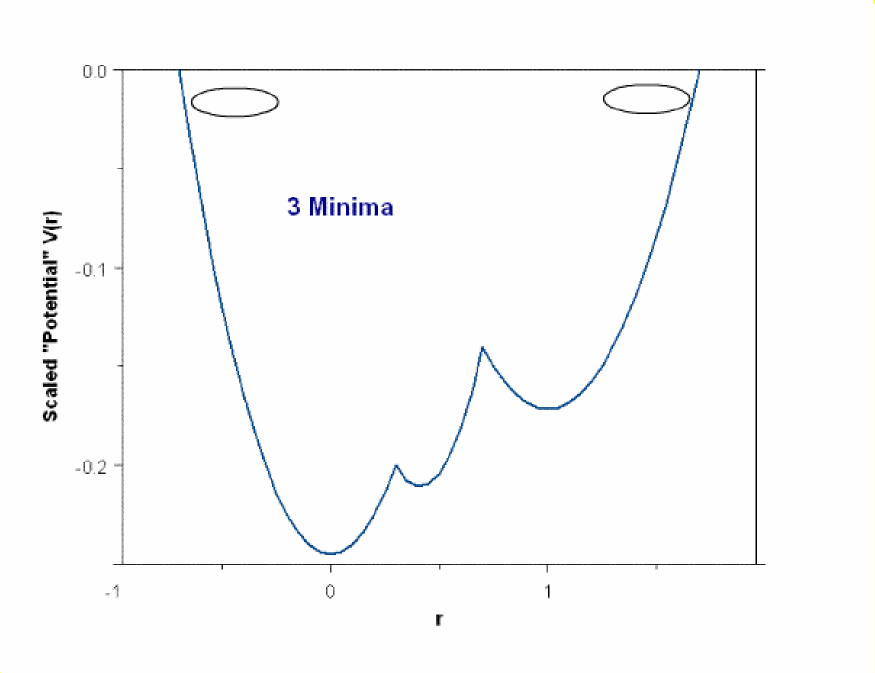
- Extrema are the positions of the stable cones; gradient is "force" that pushes trial cone to the stable cone, *i.e.*, the flow vector

$$\vec{F}(\vec{r}) = -\vec{\nabla}V(\vec{r}) = \sum_i E_T^i \left(\vec{r}^{\,i}-\vec{r}\right)\Theta\left(R^2-\left(\vec{r}^{\,i}-\vec{r}\right)^2\right)$$

(THE) Simple Theory Model - 2 partons (separated by < 2R): yield potential with 3 minima – trial cones will migrate to minima from seeds near original partons

⇒ miss central minimum





$z = p_{\min} / p_{\max}$, r = separation

Smearing of order R

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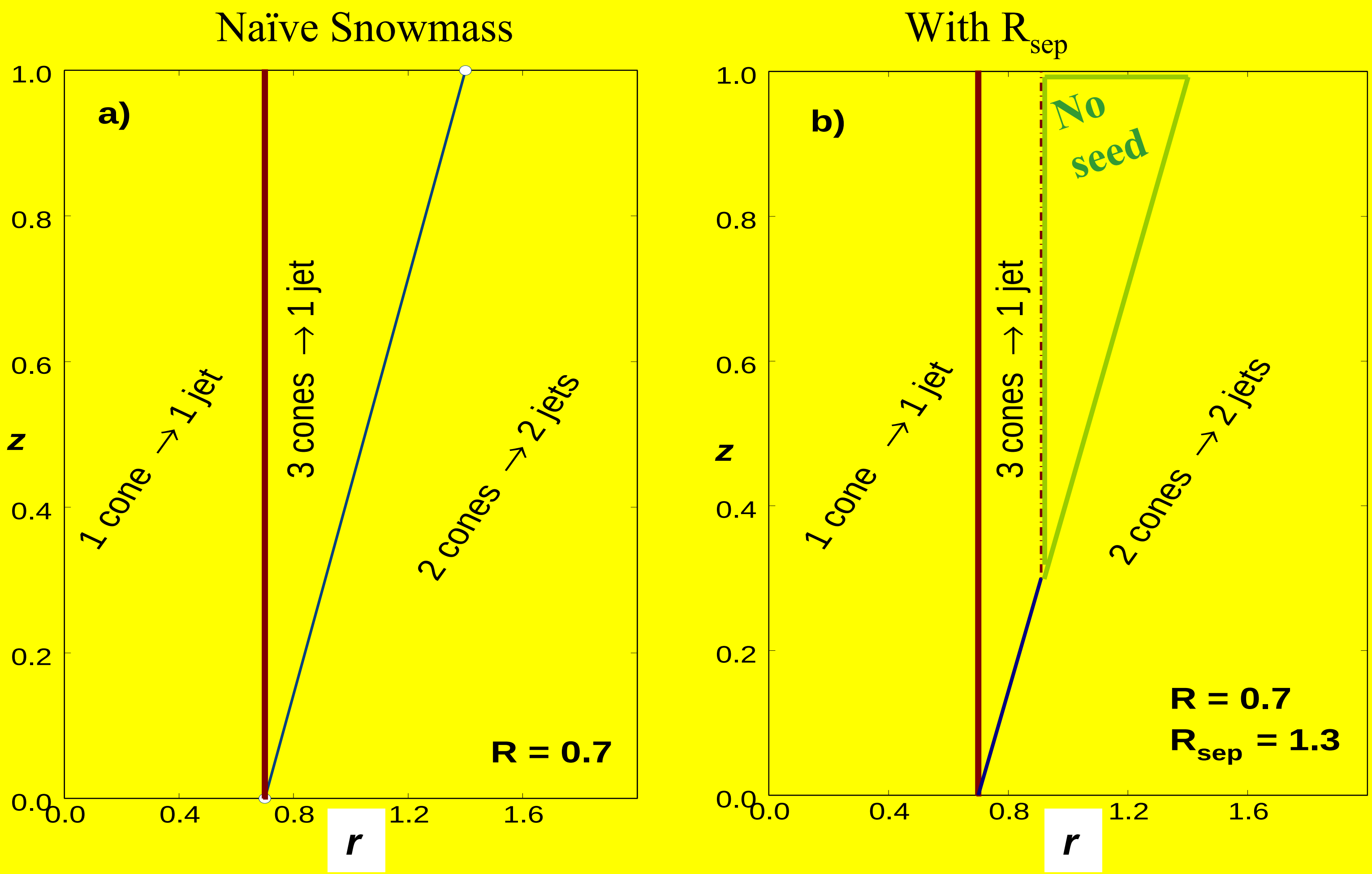
⇒"simulate" with R_{SEP} parameter in theory

NLO Perturbation Theory – r = parton separation, $z = p_2/p_1$

R_{sep} simulates the cones missed due to no middle seed



Run I Issues (Life gets more complex):

Cone: <u>Seeds</u> – only look for jets under brightest street lights, *i.e.*, near very active regions

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⇒ <u>Different</u> in different experiments

⇒ Don't find "possible" central jet between two well separated proto-jets (partons)

⇒"simulate" with R_{SEP} parameter in theory

Kinematic variables: $E_{T,Snow} \neq E_{T,CDF} \neq E_{T,4D} = p_T$ – Different in different experiments and in theory

“HIDDEN” issues, detailed differences between experiments

- **Energy Cut on towers kept in analysis (*e.g.*, to avoid noise)**
- **(Pre)Clustering to find seeds (and distribute “negative energy”)**
- **Energy Cut on precluster towers**
- **Energy cut on clusters**
- **Energy cut on seeds kept**

+ Starting with seeds find stable cones by iteration, but in JETCLU (CDF), “once in a seed cone, always in a cone”, the <u>“ratchet”</u> effect

[Don’t hide the details!!!!]

Detailed Differences mean Differences in:

- UE contributions
- Calorimeter info *vs* tracking info
- Non-perturbative hadronization (& showering) compared to PertThy
- (Potential) Impact of Higher orders in perturbation theory
- Mass reconstruction

To address these issues, the Run II Study group Recommended

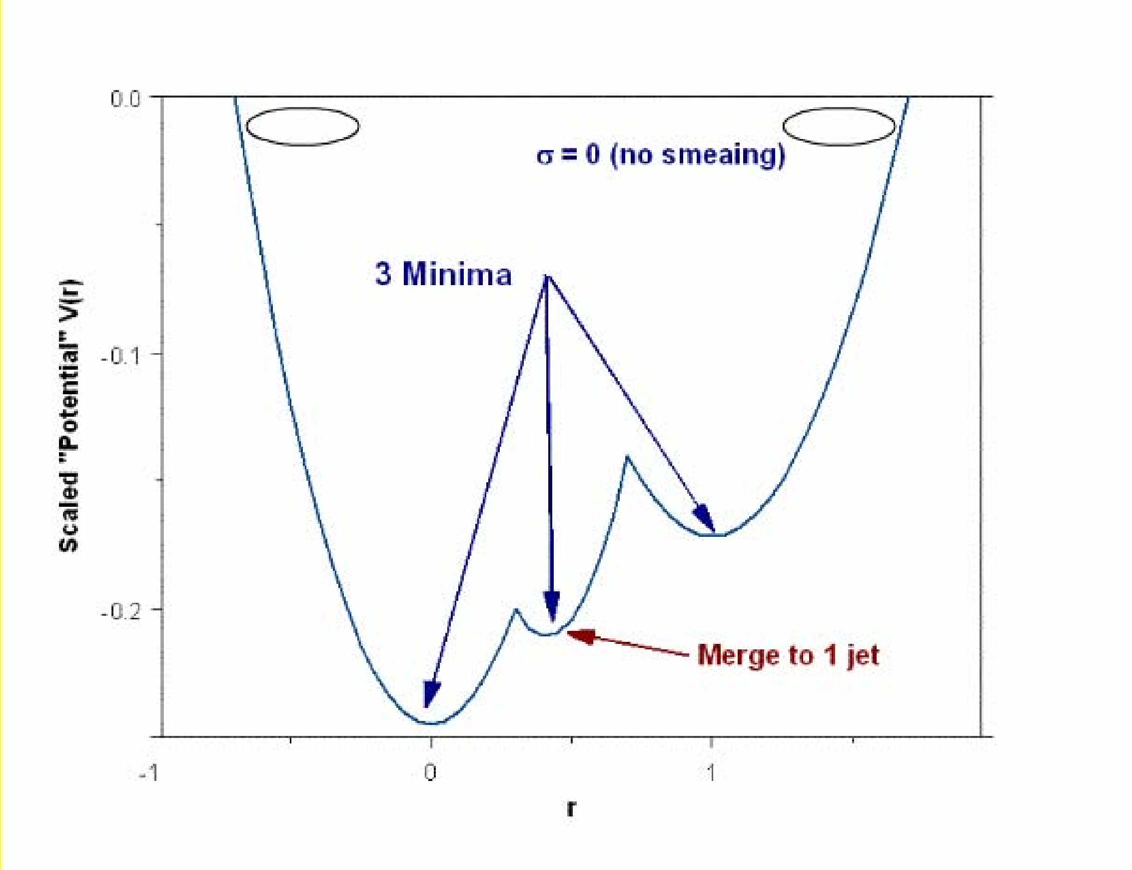
Both experiments use

- **(legacy) Midpoint Algorithm – always look for stable cone at midpoint between found cones**
- **Seedless Algorithm**
- **k_T Algorithms**

- **Use identical versions except for issues required by physical differences (in preclustering??)**

- **Use (4-vector) E-scheme variables for jet ID and recombination**

Consider the corresponding "potential" with 3 minima, expect via MidPoint or Seedless to find middle stable cone



k_T Algorithm

- **Combine partons, particles or towers pair-wise based on "closeness" in momentum space, beginning with low energy first.**
- **Jet identification is unique – no merge/split stage**
- **Resulting jets are more amorphous, energy calibration difficult (subtraction for UE?), and analysis can be very computer intensive (time grows like N^3)**

Streamlined Seedless Algorithm

- **Data in form of 4 vectors in (η,φ)**
- **Lay down grid of cells (~ calorimeter cells) and put trial cone at center of each cell**
- **Calculate the centroid of each trial cone**
- **If centroid is outside cell, remove that trial cone from analysis, otherwise iterate as before**
- **Approximates looking everywhere; converges rapidly**
- **Split/Merge as before**

Use common Split/Merge Scheme for Stable Cones

- Process stable cones in decreasing energy order, pair wise

- f_{merge} = 0.50% (< 0.75% in JETCLU);
  Merge if shared energy > f_{merge}, Split otherwise

- Split/Merge is iterative, starting again at top of reordered list after each split/merge event ($\neq$ JETCLU which is a “single-pass” scheme, no reordering)

  $\Rightarrow$ Enhance the merging fraction wrt JETCLU (see later) Is this too much, a “vacuum cleaner”?

A NEW (old) issue for Midpoint & Seedless Cone Algorithms

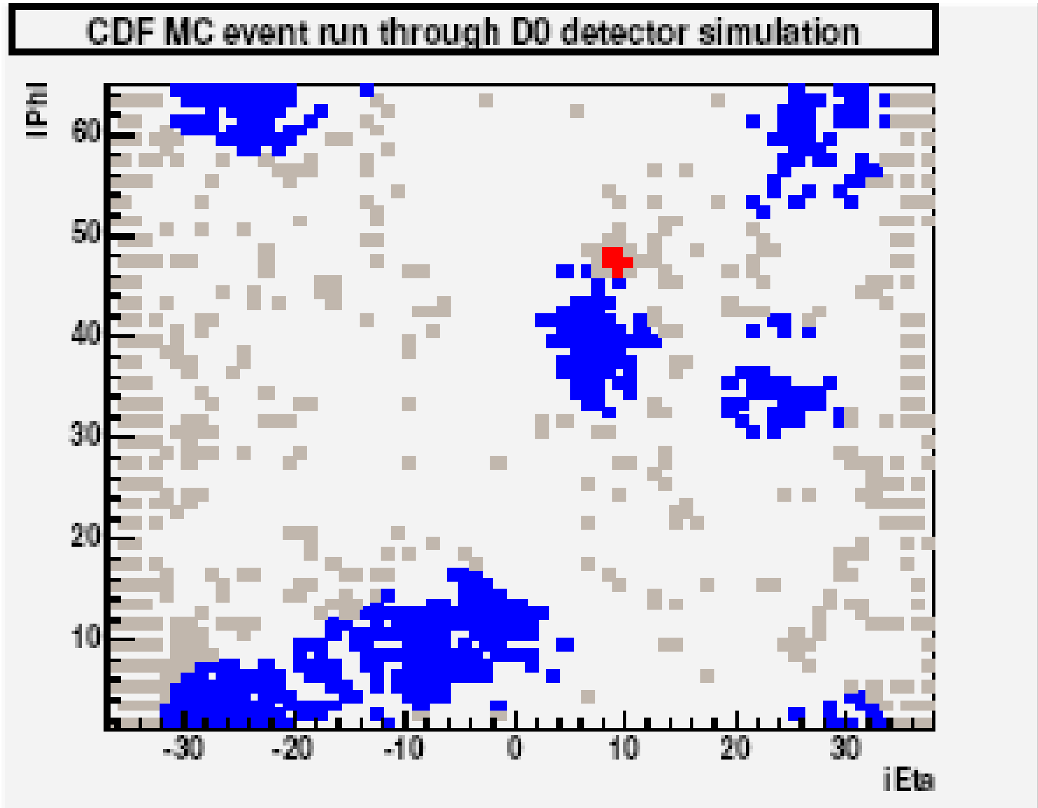
- Compare jets found by JETCLU (with ratcheting) to those found by MidPoint and Seedless Algorithms

- "Missed Energy" – when energy is smeared by showering/hadronization do not always find stable cones expected from perturbation theory

  $\Rightarrow$ 2 partons in 1 cone solutions
  $\Rightarrow$ or even second cone

Under-estimate E_T – new kind of Splashout

Missed Towers (not in any stable cone) – How can that happen? Does DØ see this?



- RunII cone $R = 0.7$
- Jet towers
- Unclustered towers $pT < 2GeV$
- Unclustered towers $pT > 2GeV$

We see it too!

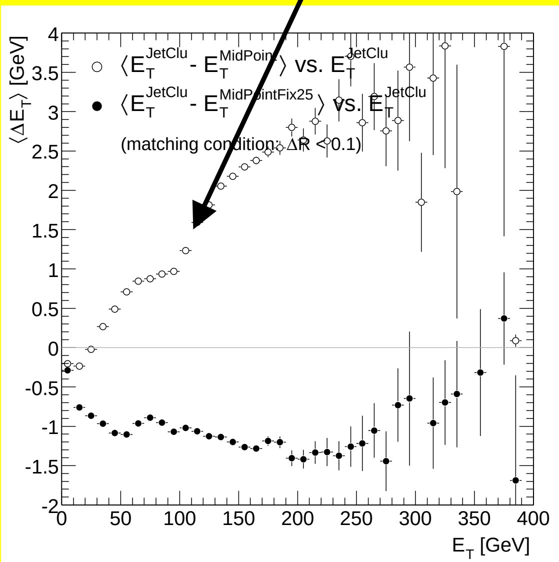
From Zdenek Hubacek (**DØ**)

Match jets found by 2 algorithms, Compare E_T

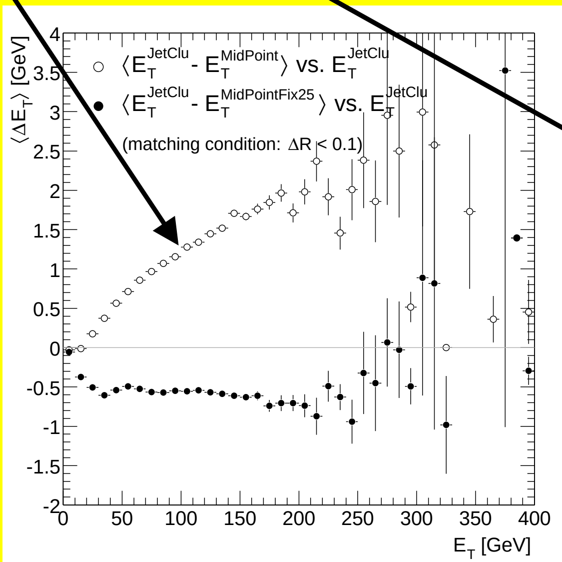
Lost Energy $E_T^{MidPoint} < E_T^{JETCLU}$!?

$(\Delta E_T/E_T \sim 1\%,\ \Delta\sigma/\sigma \sim 5\%)$

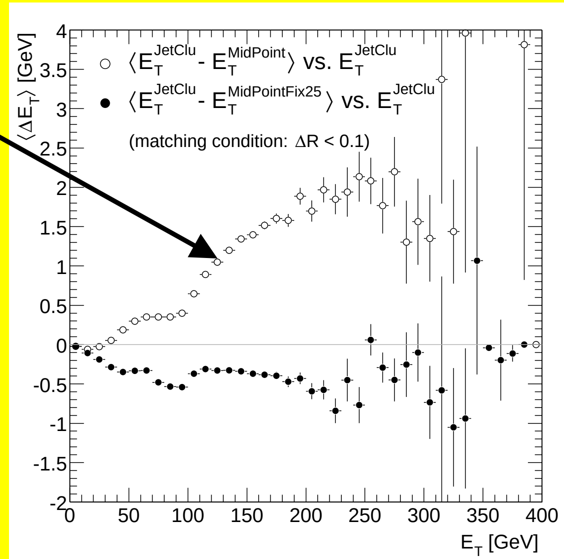
Partons



Calorimeter



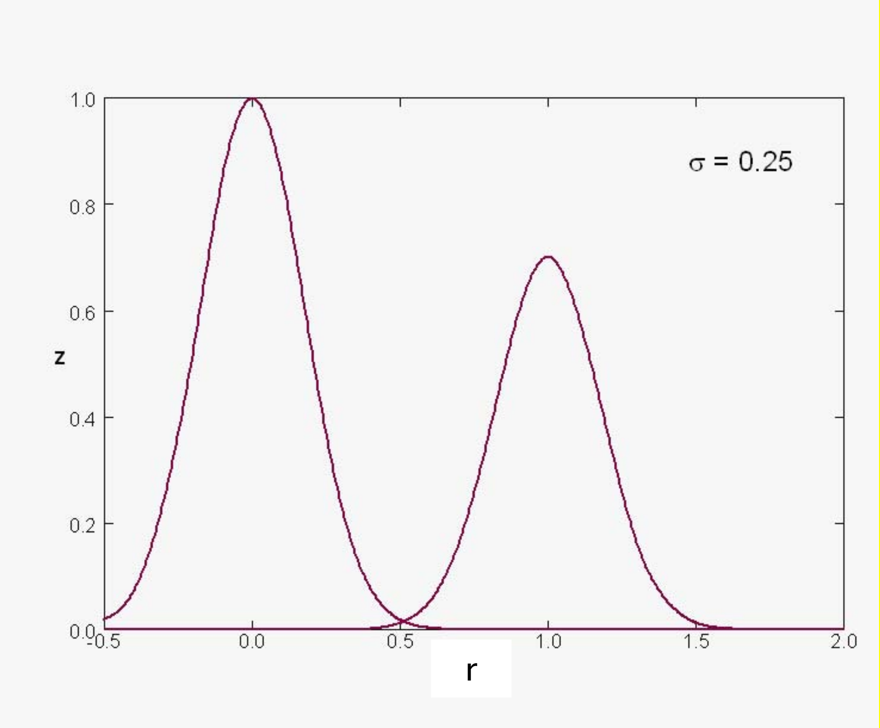
Hadrons

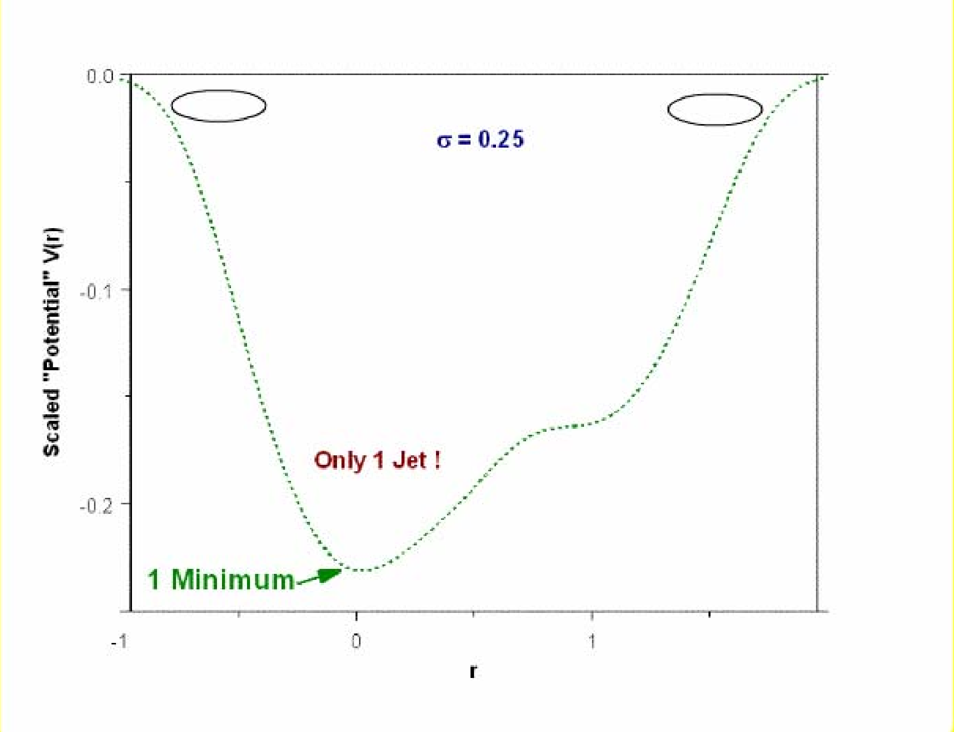


This must effect mass reconstruction;
Note Differences between graphs

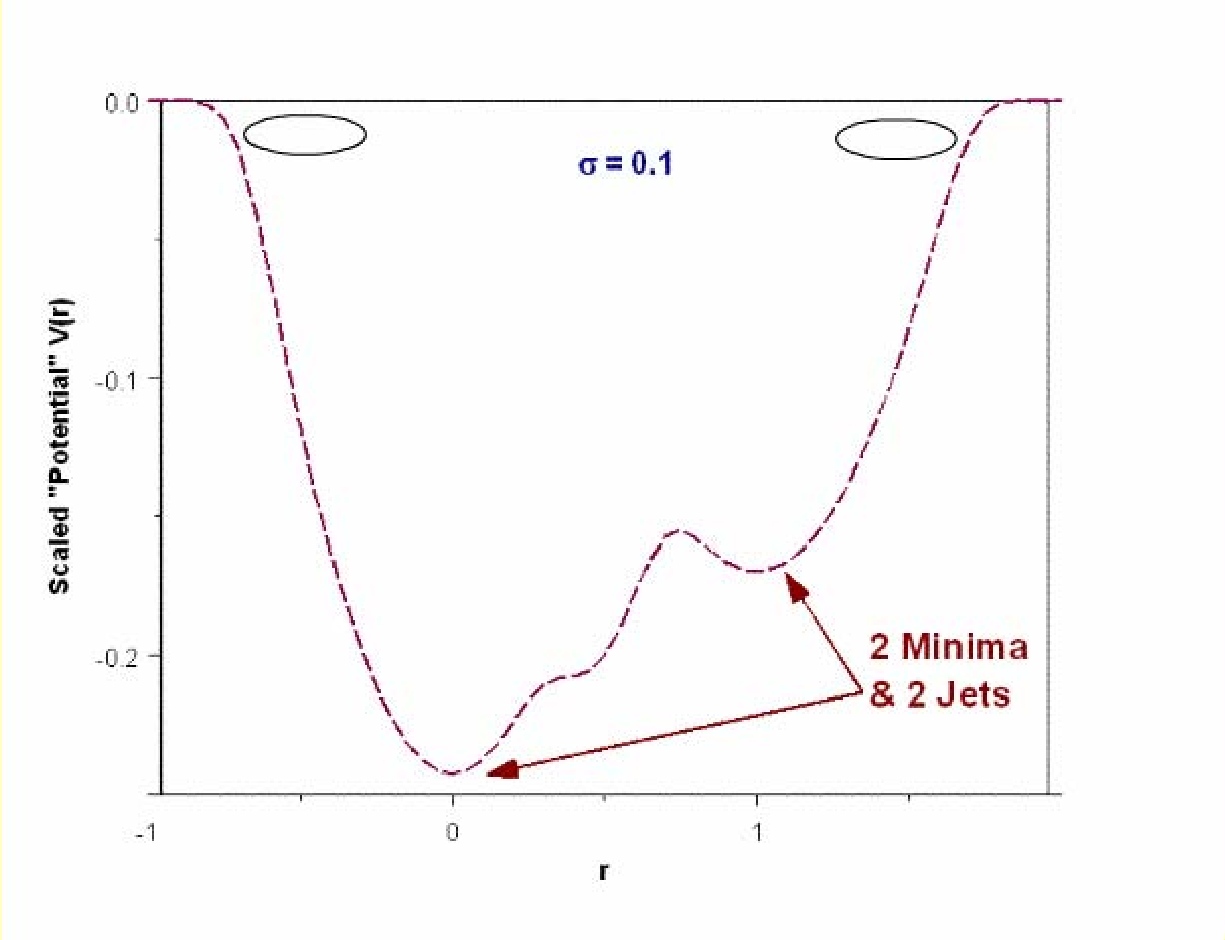
Results from M. Tönnesmann

Include smearing (~ showering & hadronization) in simple picture, find only 1 stable cone





Even if 2 stable cones, central cone can be lost to smearing

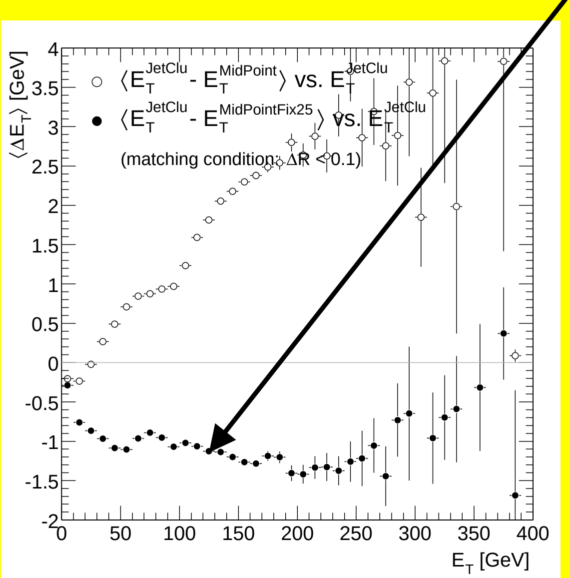


Search Cone "Fix" advocated by CDF, *i.e.*, Joey the H.

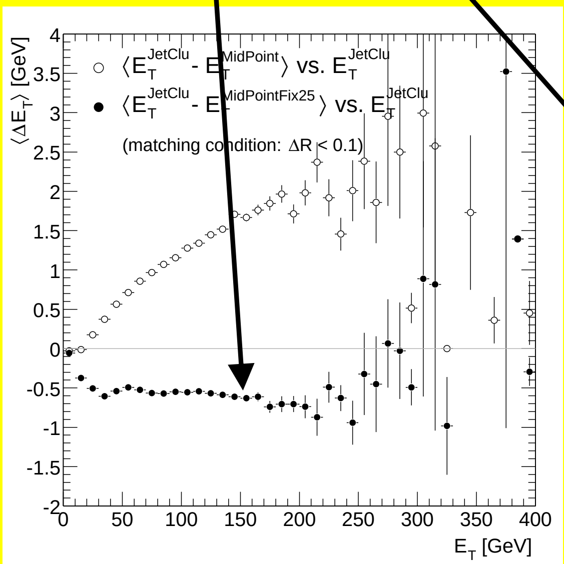
- Consider 2 distinct steps:
  - Find Stable cones
  - Construct Jets (split/merge, add 4-vectors)
- Use $R' < R$, *e.g.*, $R/2$, during stable cone search, less sensitivity to smearing, especially energy at periphery $\Rightarrow$ more stable cones
- Use R during jet construction (not required to be stable)
- Due to increased number of cones, use $f = 0.75$ to avoid fat jets (over merging).

(Over)Found Energy!? $E_T^{MidPoint} > E_T^{JETCLU}$

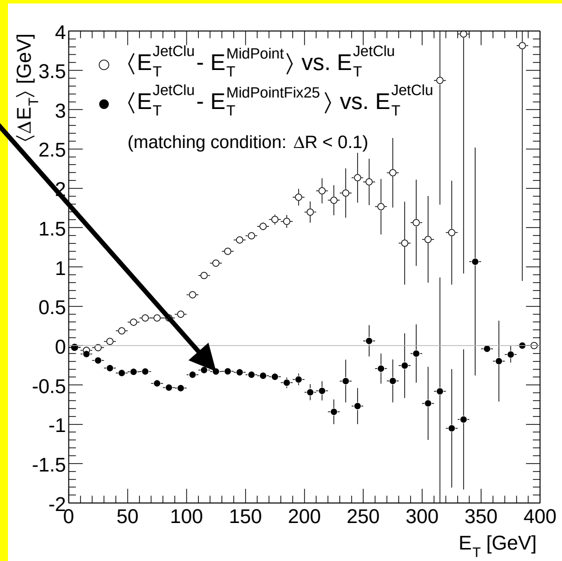
Partons



Calorimeter

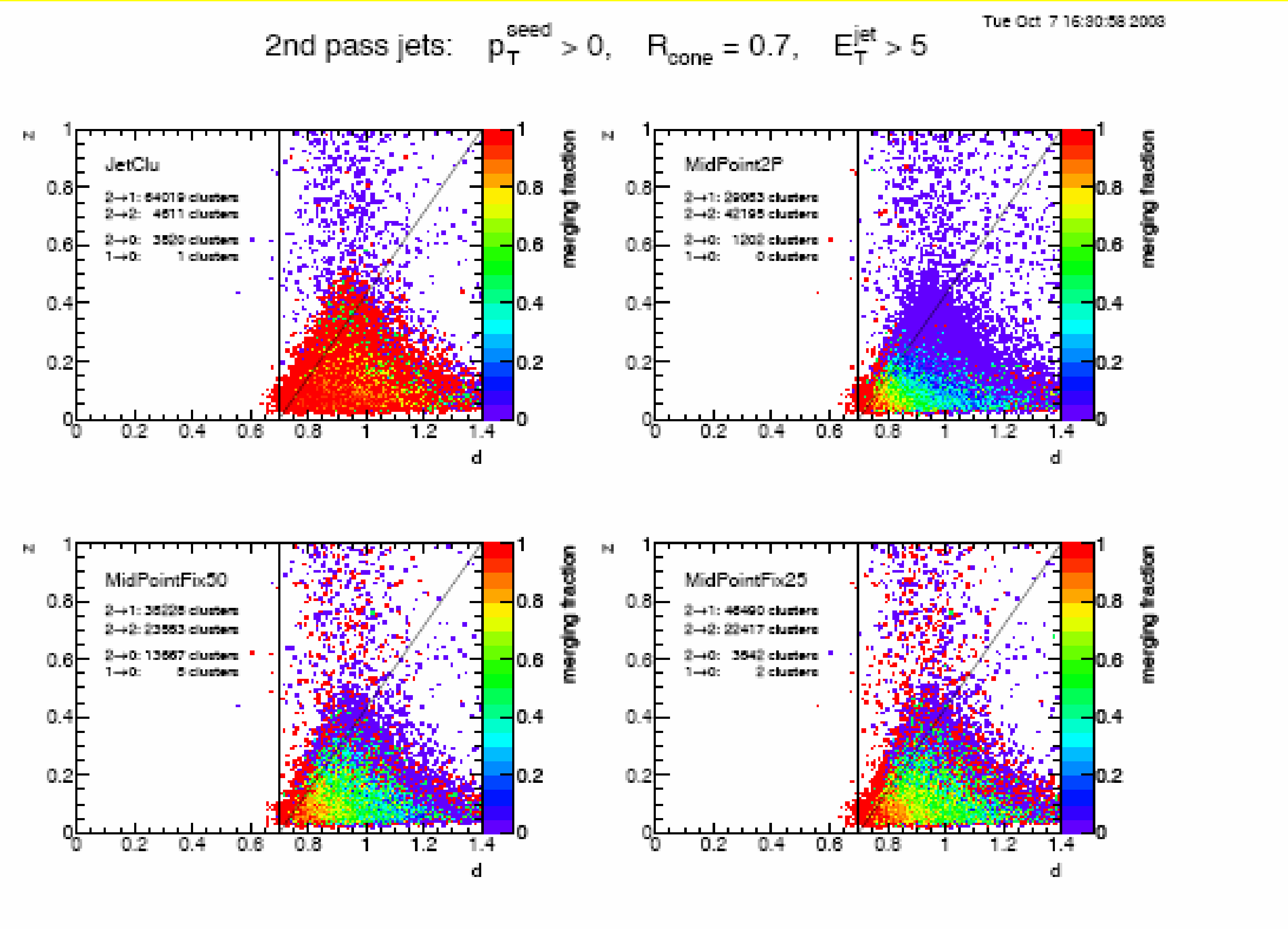


Hadrons



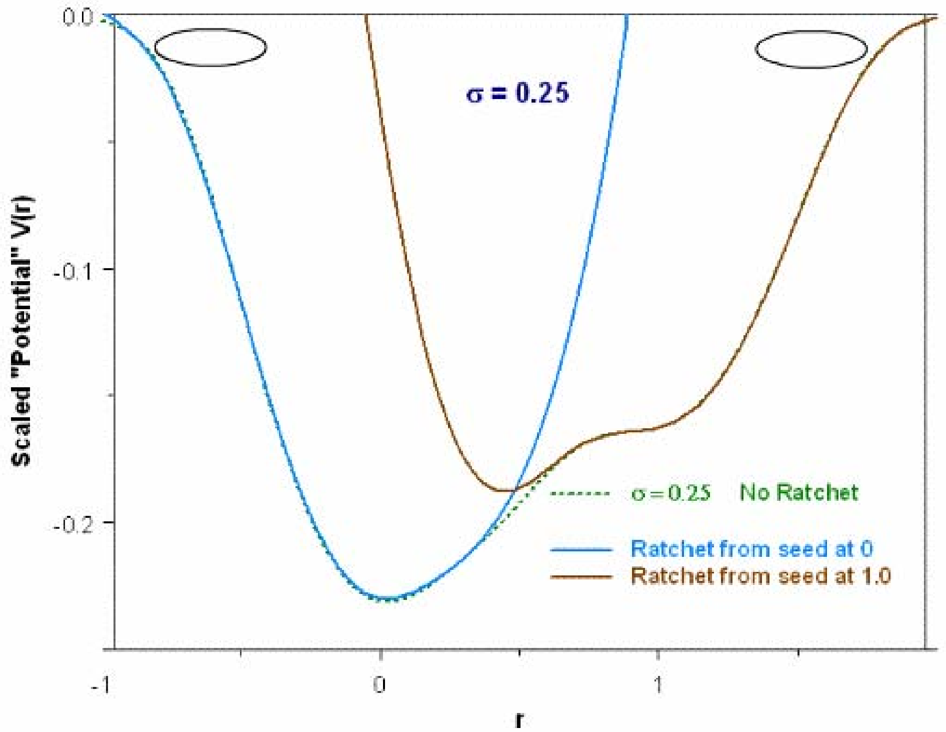
Note Differences

1^{st} pass jets = found by Midpoint
2^{nd} pass jets = missed by Midpoint (but found if remove 1^{st} jet)



Racheting – Why did it work?
Must consider seeds and subsequent migration history of trial cones – yields separate potential for each seed

INDEPENDENT of smearing, first potential finds stable cone near 0, while second finds stable cone in middle (even when right cone is washed out)! ~ NLO Perturbation Theory!!



But Note – we are "fixing" to match JETCLU which is *NOT* the same as perturbation theory.

Plus final cones are not stable, unless we "remove" smearing.

Unnatural? Does this meet our goal?

⇒ HW – Answers still unclear!

Can we reach the original goal of precisely mapping experiment onto short-distance theory? Using:

- MidPoint Cone algorithms (with FIX)?
- Seedless Cone Algorithm?
- k_T algorithm?
- Something New & Different, *e.g.*, Jet Energy Flows?

Can we agree to use the **SAME** Algorithm??

Extras

Think of the algorithm as a "microscope" for seeing the (colorful) underlying structure -

Overlap: stable cones must be split/merged

Depends on overlap parameter f_{merge}

Order of operations matters

All of these issues impact the content of the "found" jets

- Shape may not be a cone
- Number of towers can differ, *i.e.*, different energy
- Corrections for underlying event must be tower by tower

For example, consider 2 partons: $p_1 = z p_2$

$$E_{T,scalar} = E_{T,Snow} = p_1 + p_2$$

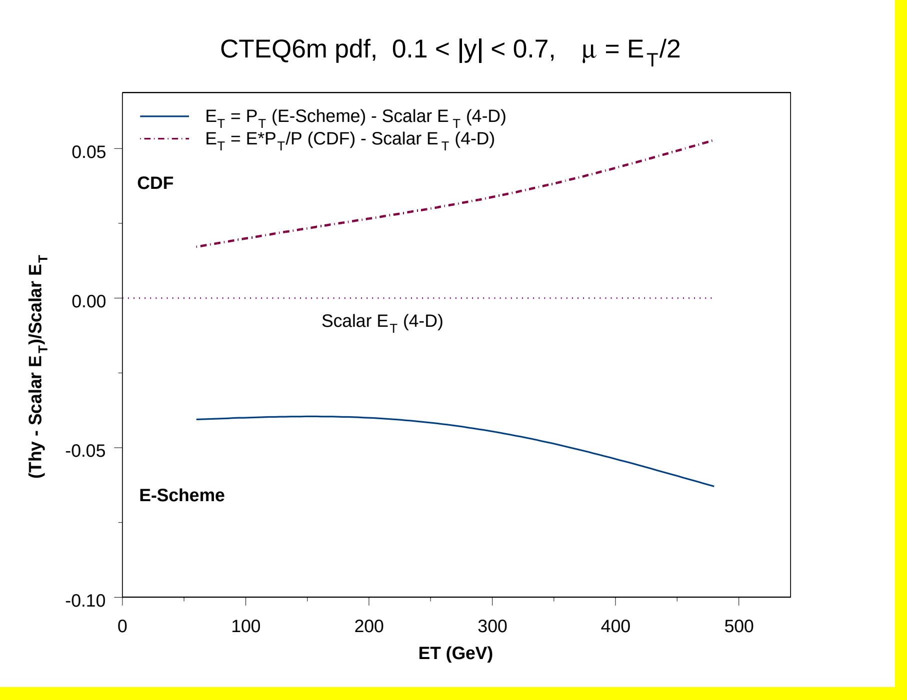
$$E_{T,4D} \equiv \left| \vec{P}_{J,T} \right| = \sqrt{p_1^2 + p_2^2 + 2 p_1 p_2 \cos\Delta\phi}$$

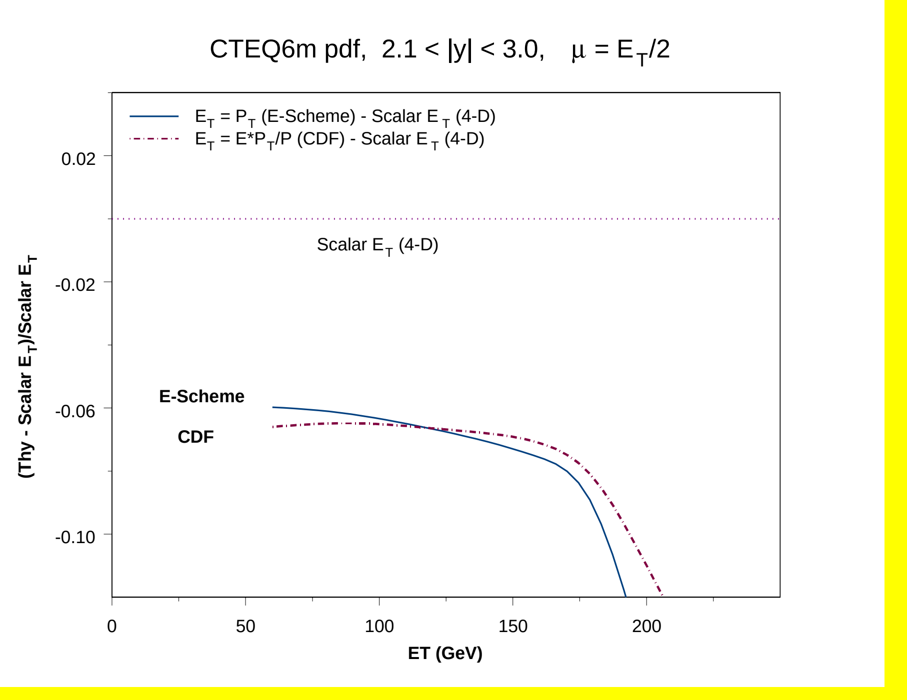
$$= E_{T,Snow} \frac{\sqrt{1 + z^2 + 2z\cos\Delta\phi}}{1+z} \leq E_{T,Snow}$$

$$E_{T,CDF} \equiv E_J \sin\theta_J = E_J \frac{\left|\vec{P}_{J,T}\right|}{\left|\vec{P}_J\right|} = E_{T,4D} \frac{\sqrt{\left|\vec{P}_J\right|^2 + M_J^2}}{\left|\vec{P}_J\right|} \geq E_{T,4D}$$

$\Rightarrow$ **mass dependence – the soft stuff**

5% Differences (at NLO) !!





(see later)

Fundamental Issue

Warning:

We must all use the same algorithm!!

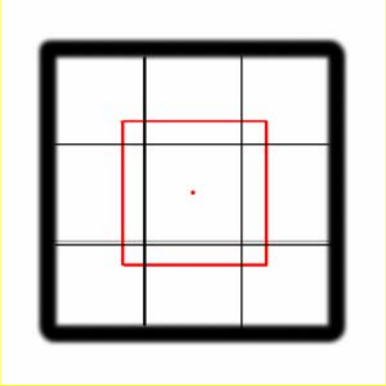
(as closely as humanly possible), *i.e.* both ATLAS & CMS.

Streamlined Seedless Algorithm

- **Data in form of 4 vectors in (η,φ)**
- **Lay down grid of cells (~ calorimeter cells) and put trial cone at center of each cell**
- **Calculate the centroid of each trial cone**
- **If centroid is outside cell, remove that trial cone from analysis, otherwise iterate as before**
- **Approximates looking everywhere; converges rapidly**
- **Split/Merge as before**

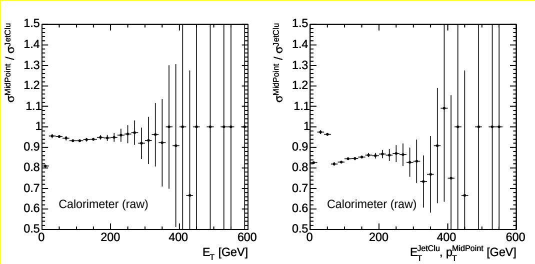
Run II Issues

- k_T – "vacuum cleaner" effect accumulating "extra" energy – Does it over estimate E_T?
- "Engineering" issue with streamlined seedless – must allow some overlap or lose stable cones near the boundaries (M. Tönnesmann)



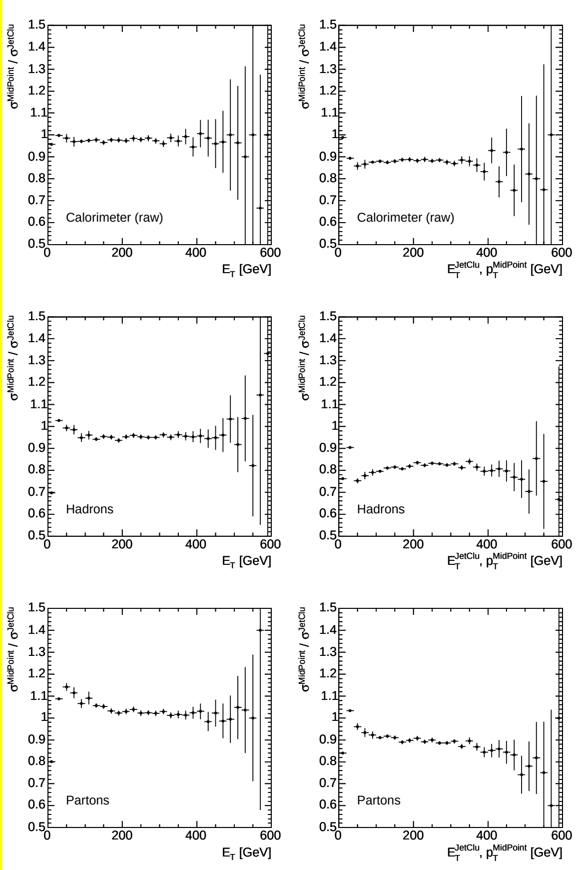
$\sigma_{MidPoint}/\sigma_{JetClu}$

DATA

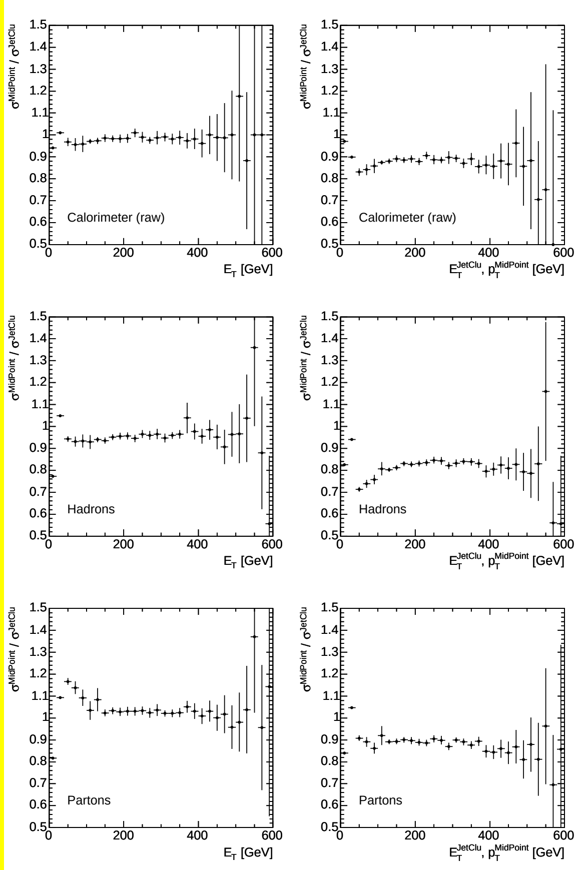


Result depends on choice of variable & MC

HERWIG



PYTHIA



Cal

Had

Par

Note Differences

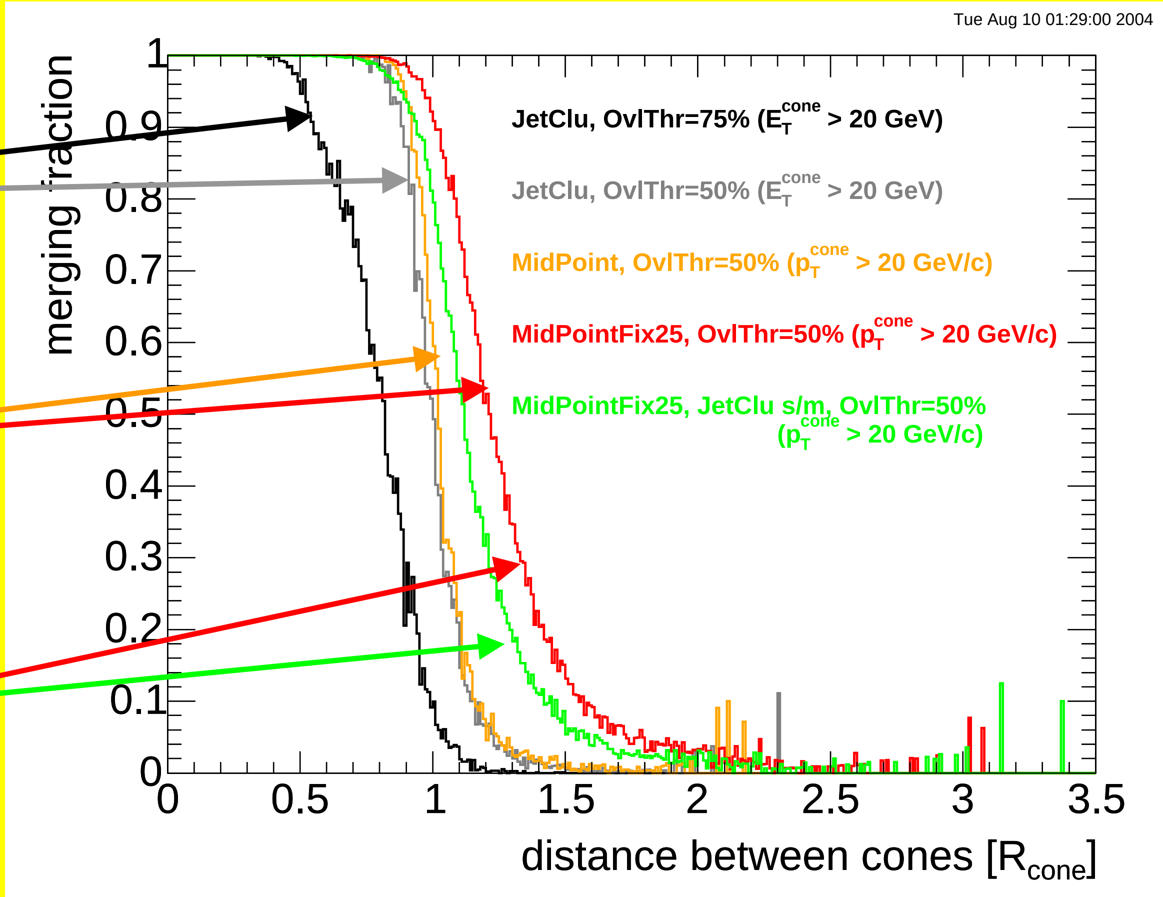
Results from M. Tönnesmann

But underlying Structure is Different – Consider Cone Merging Probability

Result depends on f_{merge}

Result depends on "FIX"

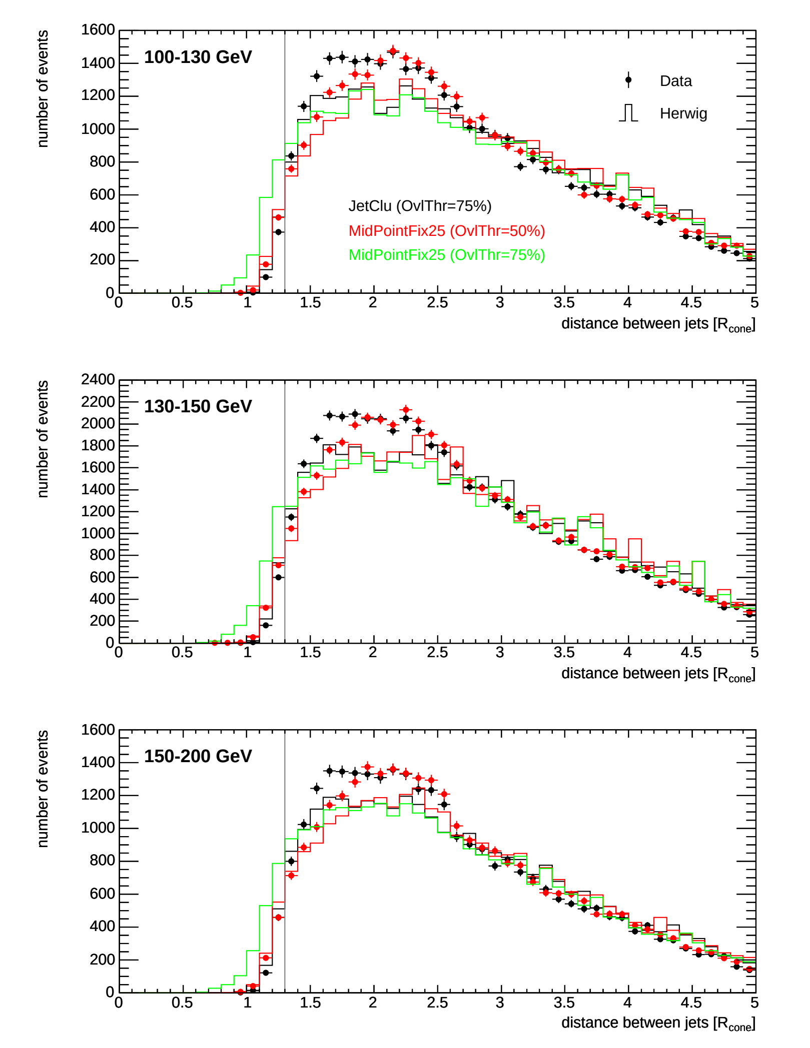
Result depends on ordering in S/M



But found jet separation looks more similar:

Conclude stable cone distributions must differ to match (cancel) the effects of merging

Jet dist ~ (Stable Cone) * (Merge Prob)



Each event produces a JEF *distribution*, *not* discrete jets

- Each event = list of 4-vectors $\left\{p_\mu^i\right\}_{i=1}^N = \left\{\left(E^i, \vec{P}^i\right)\right\}_{i=1}^N$
- Define 4-vector distribution $P_\mu\left(\hat{P}\right) = \sum_{i=1}^N p_\mu^i \delta\left(\hat{P} - \hat{P}^i\right)$
  where the unit vector $\hat{P} = \vec{P}/\left|\vec{P}\right|$ is a function of a 2-dimensional angular variable $m = \left(y, \phi\right)$
- With a "smearing" function $A(m), \int d^2m\, A(m) = 1$

e.g., $A(m) = \dfrac{\Theta\left(R^2 - y^2 - \phi^2\right)}{\pi R^2}$

We can define JEFs

$$J_\mu(m) \equiv \int d^2m'\, P_\mu(m') \times A(m-m')$$

or

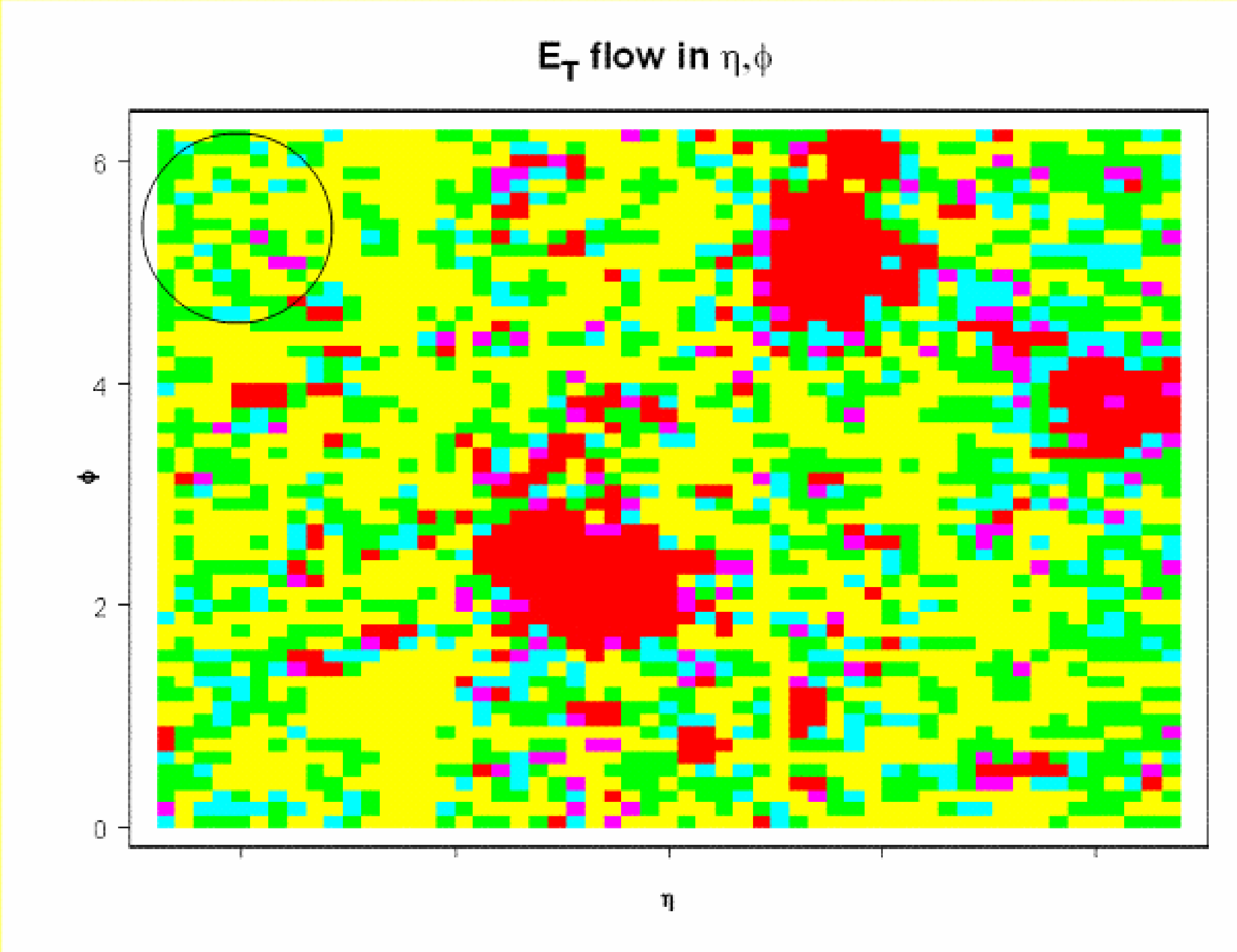
$$J_T(m) = \int d^2m' \sqrt{P_x^2(m') + P_y^2(m')} \times A(m-m')$$

Corresponding to $E_T = \pi R^2 \times J_T$

The Cone jets are the same function evaluated at the **discrete** solutions m_j of (stable cones)

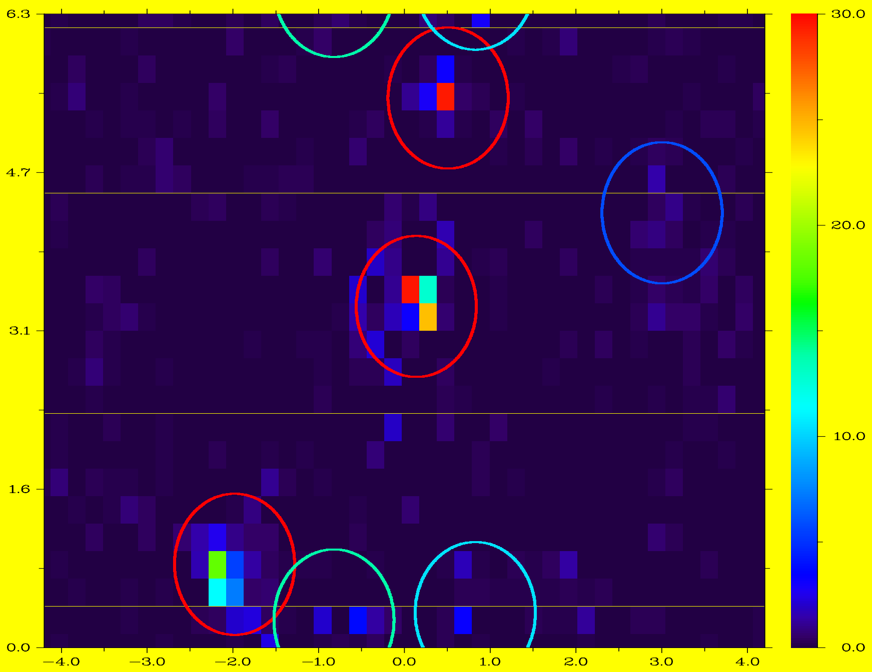
$$\int d^2m' \sqrt{P_x^2(m') + P_y^2(m')} \times A(m_j - m') \times (m_j - m') = 0$$

Simulated calorimeter data & JEF



“Typical” CDF event in y, ϕ

Found cone jets



JEF distribution